Towards Development of Sustainable Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

Spyridon A. Paschalis[1](✉), Andreas P. Lampropoulos[2], and Joseph P. Rizzuto[1]

[1] University of West London, London, UK
Spyros.Paschalis@uwl.ac.uk
[2] University of Brighton, Brighton, UK

Abstract. Climate change is one of the main problems that our planet faces. A challenging issue in the Civil Engineering field is to produce more sustainable materials and structures. Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is cementitious material with advantageous mechanical properties. UHPFRC can be used in a number of applications that require high-strength, ductility and durability. In the production of UHPFRC large quantities of cement, aggregates and steel fibers are required. In this investigation, Ground Granulated Blast Furnace Slag (GGBS) has been used as partial replacement of cement to produce a more sustainable UHPFRC. In addition, general purpose unprocessed recycled steel fibers have been used as an alternative to conventional new steel fibers. A comparison is made of the different types of fibers used. The results of the present study indicated that the compressive strength of HPFRC is not affected significantly for GGBS contents up to 30%. The addition of unprocessed recycled steel fibers resulted in an increase in the compressive strength of UHPFRC. In tension, the UHPFRC material presented strain softening and with an overall lower strength compared to using conventional fibers. As long fibers tend to become entangled, in the present study short recycled fibers have been used. Further study is required to investigate the use of suitably treated recycled fibers of various lengths.

Keywords: Sustainability · Cement Replacement · UHPFRC · Recycled fibers · Sustainable Materials

1 Introduction

During the last century our planet has faced some great challenges such as climate change, global warming, damage of ozone layer and the reduction of natural resources. It has become essential therefore to minimize the consumption of natural resources and to reduce the negative environmental impact from human activities. A challenging issue in the field of Civil Engineering is to produce more sustainable materials and structures. Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a material with advantageous mechanical properties. UHPFRC can be used in structural applications

A. Jędrzejewska et al. (Eds.): SynerCrete 2023, RILEM Bookseries 44, pp. 865–875, 2023.
https://doi.org/10.1007/978-3-031-33187-9_79

that require the construction of thin elements with high strength, ductility and durability. Despite the excellent mechanical properties, UHPFRC is a material that presents disadvantages in its use such as (i) the high cost, and (ii) high quantities of cement, fibres and fine sand are required. (Paschalis and Lampropoulos [1]).

In the present investigation, an attempt is made to produce a more environmentally friendly UHPFRC without significant loss of the mechanical properties of the material.

2 Literature Review

Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) is a material characterized by compressive strength higher than 150 MPa, ductility and strain hardening behaviour in tension. This is achieved by the incorporation of high volume of fibers, normally higher than 2 Vol. %. (AFGC, [2]). A characteristic of UHPFRC is the enhanced microstructure of the material. For the preparation of the UHPFRC, only fine materials are used such as fine sand, silica fume, high strength cement together with superplasticizer and water.

There are several studies on the investigation of properties of this material. Nicolaides et al. [3] developed an optimum UHPFRC mix against blast and impact loading with the materials available in Cyprus. In their study, different parameters were investigated such as: fiber content, different water cement ratios, different curing conditions and various types of sand. The optimum mix design had a water-binder ratio of 0.16, 6 Vol.% steel fibers and was cured for 11 days by steam curing.

Abbas et al. [4] observed that UHPFRC presented higher load carrying capacity with the use of short fibers compared to long fibers. Ferrara et al. [5] highlighted the importance of fibers orientation in the performance of UHPFRC. In this study, slabs and beam were prepared in different flow directions. It was found that the specimens with fiber alignment parallel to the flow direction presented a better performance.

Paschalis and Lampropoulos [6] investigated the effects of fiber contents and curing regimes on the tensile properties of UHPFRC. In their study, different stress-strain models for tension were proposed for different fiber contents. In addition, it was found that 7 days of heat curing can result in strengths which can be achieved in 90 days with normal curing conditions.

UHPFRC has been used in a number of applications that require high strength and ductility. A promising application of UHPFRC is for the repair and strengthening of Reinforced Concrete (RC) structures. Safdar et al. [7] found that strengthening by applying layers of UHPFRC resulted mainly in an increase in the stiffness of the repaired elements. Paschalis and Lampropoulos [8] applied UHPFRC as a strengthening material and investigated different configurations which included strengthening with UHPFRC layers and with and without dowels and UHPFRC jackets. It was found that the strengthened members using UHPFC jackets presented the optimum performance, while the inclusion of dowels resulted in near monolithic behaviour. Bruhwiler and Denarie [9], successfully applied UHPFRC in a number of real-life applications such as crash barriers, bridge kerbs, retrofitting of bridge piers and an industrial floor. The application of UHPFRC compared to conventional concrete had significant advantages which included the excellent properties of the material.

In this investigation, an attempt is made at producing a more sustainable UHPFRC. Ground Granulated Blast-Furnace Slag (GGBS) is a material which has been used for the production of a more sustainable concrete.

The embodied CO_2 of Portland Cement CEM I is estimated at 913 kg CO_2e/tonne, while for other materials such as GGBS is 67 kg CO_2e/tonne, for fly ash 4 kg CO_2e/tonne, for limestone files 75 kg CO_2e/tonne. For the different types of cement, the embodied CO_2 is estimated at 859–745 kg CO_2e/tonne for CEM II/A, 728–615 kg CO_2e/tonne for CEMII/B, 622–398 kg CO_2e/tonne for CEMII/A and 381–277 kg CO_2e/tonne for CEM III/B. (Cementitious Slag Makers Association, [10]) These values do not include transport to concrete plant. Based on these values, the use of GGBS as partial replacement of cement or the used different types of cement such as CEM III/A,B can reduce the embodied CO_2.

Mohan and Hayat [11] investigated different percentages of GGBS as part replacement of OPC for the production of concrete. It was found that in all cases that they considered, lower strengths were achieved compared to a control mix. More specifically, for percentages of GGBS of 40%, 50% and 60%, the compressive strength decreased by 15.5%, 11.7% and 29% respectively. A similar pattern was noticed for tensile strength.

Elavarasan et al. [12] investigated the mechanical properties of concrete at different ages, for different GGBS contents in the range of 10% to 50%. The compressive strength of concrete at 28 days for 10% replacement of cement was increased by 14.3% and for 20% by 6.6%. For percentages of 30%, 40% and 50%, the compressive strength was reduced by 0.7%, 11.5% and 16.4% respectively. In their study, the tensile splitting strength and the flexural strengths were also investigated. It was found that the tensile splitting strength of concrete at 28 days for 10% replacement of cement with GGBS was increased by 10%. For percentages of 20%, 30%, 40% and 50% the tensile splitting strength was decreased by 7.4%, 21%, 31% and 35.6% respectively. The flexural strength on the other hand, for percentages of 10%, 20%, 30%, and 40% was increased by 27.6%, 10.6%, 6.4% and 2.1%. For percentage 50% the flexural strength was decreased by 2.1%.

Elchalakani et al. [13] presented a proposal for the development of sustainable concrete with a low carbon footprint using GGBS as part replacement of cement to build Masdar City in the United Arab Emirates (UAE). For this investigation, different mix designs were examined containing different percentages of GGBS in the range of 50% to 80%. For this project, a mix containing 80% GGBS and 20% CEM I was adopted and considered parameters such as the carbon footprint and the economy. The carbon footprint of this mix was estimated at 154 kg/m^3.

In this investigation recycled steel fibers from car tyres [14] have been used to produce more sustainable UHPFRC. Pilakoutas et al. [15], described the procedure to obtain steel fibers from car tyres. The first step for the production of this type of fiber is chopping the tyres to pieces in the size range of 50–150 mm. The tyre pieces are then chopped into smaller pieces and magnets are used to separate the fibers from the rubber. The rubber is then placed into a hammer mill and is cut to sizes in the range of 1–10 mm with any remaining fibres extracted using magnets.

Neocleus et al. [16], investigated the suitability of the design guidelines proposed by RILEM for Steel Fibre Reinforced Concrete (SFRC) for the flexural design of concrete using recycled fibers from tyres. The researchers found that the guidelines did not cover accurately the tensile stress-strain behaviour of this material when prepared with reclaimed fibres from tyres and different models were proposed.

Aiello et al. [17], investigated the properties of concrete using recycled steel fibres from waste tyres and parameters such as bond strength, compressive strength and flexural behaviour were investigated. Comparisons were also presented with the performance of concrete using conventional steel fibers. In their research it was found that the pull-out response, the compressive strength and the flexural post-cracking behaviour of specimens prepared with the different types of fibres was similar. An issue with the use of recycled fibers was the reduced workability. The maximum achieved volume ratio of fibres was 0.46%.

Isa et al. [18] focused on the optimisation of the characteristics of UHPFRC with recycled steel fibres from tyres and it was found that cleaning of the fibres and reduction of the short-length fibres are essential for the enhancement of the mechanical characteristics and for the development of affordable eco-efficient UHPFRC. Recycled clean steel fibres have also been successfully used for the development of rapid hardening mortar mixes [19].

Based on the existing studies the use of recycled fibers from car tyres and the use of GGBS as part replacement of cement investigations are promising and the use of clean fibres have been found to significantly enhance the mechanical performance of concrete. In the current study the use of general purpose unprocessed recycled steel fibres is examined aiming towards a cost effective sustainable UHPFRC.

3 GGBS as Part Replacement of Cement

GGBS is a by-product of making iron and is quenched in water and ground to powder. When GGBS is mixed with water, it hydrates in a similar way to OPC but is less reactive (The concrete society, [20]).

GGBS is a material which can be used as partial replacement of cement. Available cements in the market, such as CEM III, contain GGBS as well as clinker. The aim of the present investigation is to identify the optimum content of GGBS which can be used as partial replacement of cement in UHPFRC without significant loss of strength of the material. In this present investigation, it has been adopted the approach to investigate GGBS as part replacement of CEM I for the production of UHPFRC. Further research can also be conducted on the investigation of different types of cements.

This research focused on the compressive strength of the cementitious matrix for different contents of GGBS. For the preparation of the control mix, CEM I was used, together Silica Fume, fine sand with maximum particle size of 500 μm, superplasticizer and water. Since the focus of the present investigation was on the cementitious matrix, steel fibers were not incorporated in the mix. The mix design was based on Nicolaides [21] and is presented in Table 1.

Table 1. UHPFRC control mix design (Nicolaides [21])

Materials	Quantities (kg/m^3)
CEM I	880
GGBS	0
Sand	833
Silica Fume	220
Water	172
Superplasticizer	61

For the investigation of the compressive strength of UHPFRC using different percentages of GGBS, cubes with 150 mm side lengths were tested in compression. After the demoulding, the specimens were placed in a water curing tank and the samples tested at 28 days. Different percentages of GGBS have been used as part replacement of cement, namely: 0, 10%, 20%, 30% and 50% and 80%. The compressive strength for the different GGBS contents is presented in Fig. 1 and Table 2.

Table 2. Compressive strength for different percentages of GGBS

Percentage (%)	Compressive Strength at 28 days (MPa)
0	98.1
10	96.1
20	97.3
30	97.7
50	83.0
80	56.0

As can be seen from the results of Fig. 1, GGBS in the range of 0–30% does not affect the compressive strength of the material significantly. In this range a small fluctuation in the results can be noted which also may be attributed to scatter in the results. However, for higher contents, a linear reduction of the strength for higher GGBS contents was observed. This is in agreement with studies in the literature for conventional concrete. For example, Mohan and Hayat [11] observed a reduction in the compressive strength of concrete for GGBS contents higher than 40%, while Elavarasan et al. [12] noticed reduction of compressive strength for percentages higher than 30%.

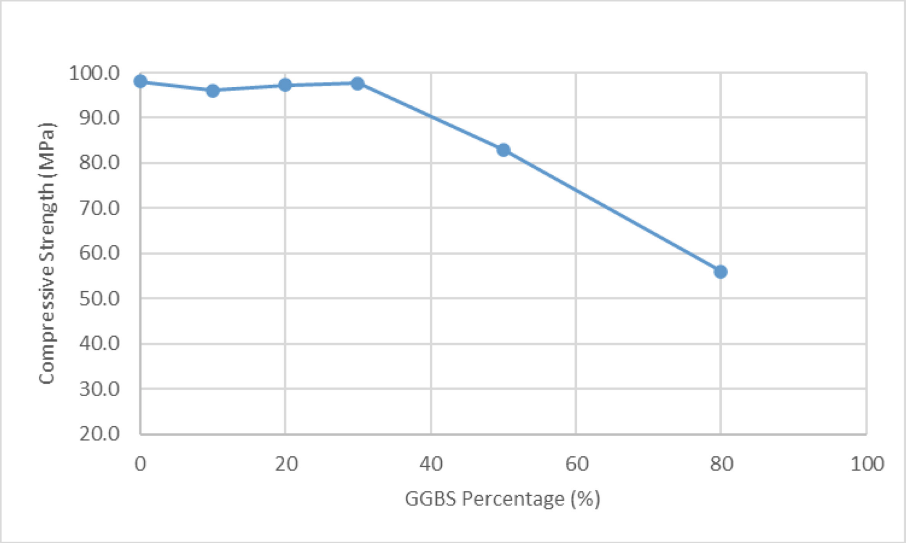


Fig. 1. Compressive strength for different percentages of GGBS

4 Investigation of Different Types of Fibers

Commonly used fibers for the preparation of UHPFRC, are straight steel microfibers with a diameter of 0.16 mm and length of 9 mm and 13 mm. One of the main disadvantages of these types of fibers, considering the amount used in the preparation of UHPFRC, is the high cost. In this present investigation, general purpose unprocessed recycled steel fibres from car tyres have been used. Based on European Tyre Association [22], more than 50 million tyres reach their end of service life in the UK every year.

Tyre shredding is used to cut tires to small pieces and magnets are employed to separate the steel from the rubber (Pilakoutas et al. [15]) As recycled fibers may contain some rubber from this procedure, washing is required before the incorporation of the fibres in the mixture. The retained fibers may have different shapes and sizes (Fig. 2). As long fibers tend to become entangled only shorter fibers have been used in the present study.

In the present investigation, two different percentages of recycled steel fibers have been used namely, 3% and 6%. Direct tensile tests and compressive tests were conducted at 28 days to obtain the material properties for different fiber contents. The experimental setup for the direct tensile tests was identical as presented by Paschalis and Lampropoulos [8]. The setup is presented in Fig. 3.

The results are presented in Figs. 4a and 4b respectively.

Based on the average curve of Fig. 4a, the average tensile strength of the specimens with 3% recycled steel fibers was found to be equal to 7.6 MPa and the modulus of elasticity was 56 GPa. The average compressive strength was found to be equal to 167 MPa.

Fig. 2. Reclaimed Steel Fibers

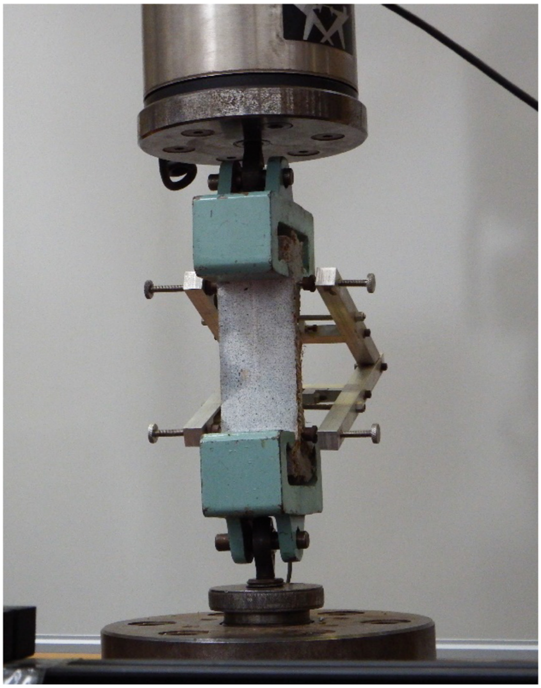
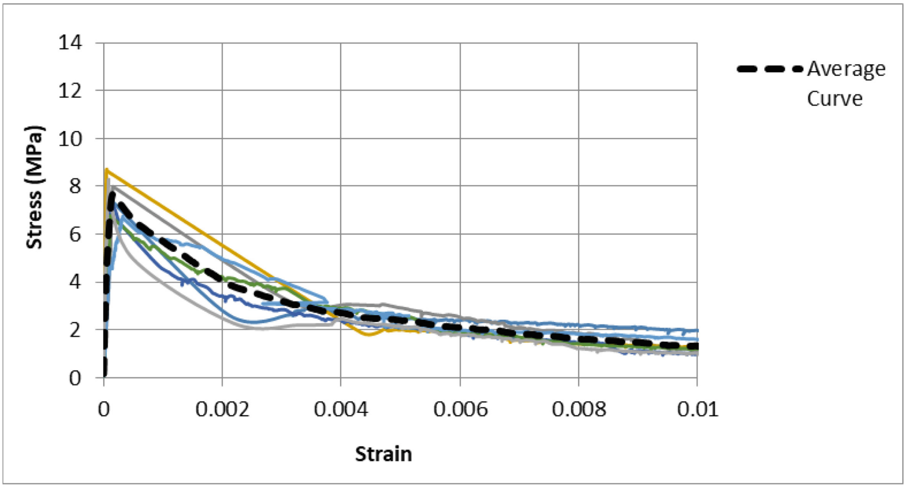


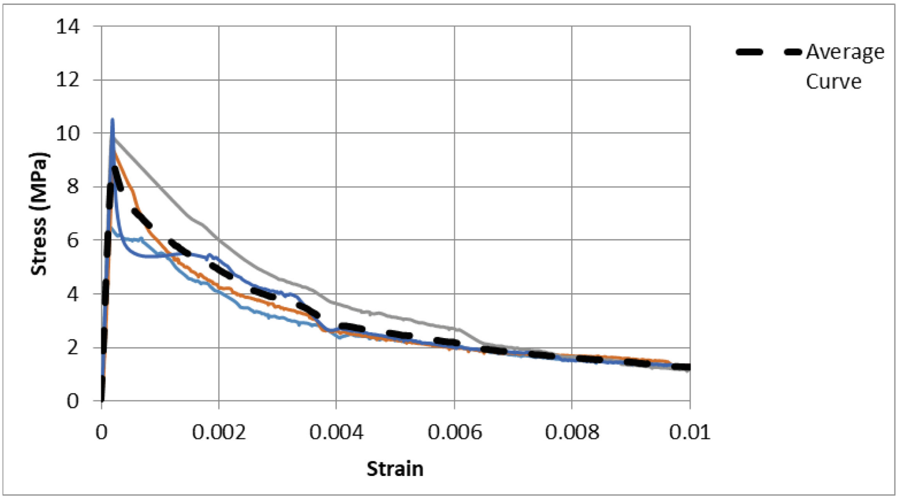
Fig. 3. Direct Tensile Tests

Based on the results of Fig. 4b, the average maximum tensile strength of specimens with 6% recycled steel fibers was equal to 8.9 MPa, the modulus of elasticity was 57 GPa and average compressive strength was 184 MPa.

To evaluate the effectiveness of the use of recycled fibers, additional UHPFRC specimens with 3% conventional steel fibers have been examined and comparisons of the behaviour in tension are presented in Fig. 5.



a)



b)

Fig. 4. Experimental results for the direct tensile tests using a) 3% recycled steel fibers and b) 6% recycled steel fibers

The results from Fig. 5, indicate that tensile performance of UHPFRC with using conventional steel fibers is significantly higher. The average maximum strength of the specimens with 3% conventional fibers was found to be equal to 10.7 MPa, the modulus of elasticity was 56 GPa and the mean compressive strength was 164 MPa.

These results are summarised and presented in Table 3.

From the results of Fig. 5 and Table 3 it is clear that UHPFRC presents strain hardening behaviour, with an overall better performance in tension with the use of conventional steel fibers. In this case and after the formation of cracks, the conventional steel fibers

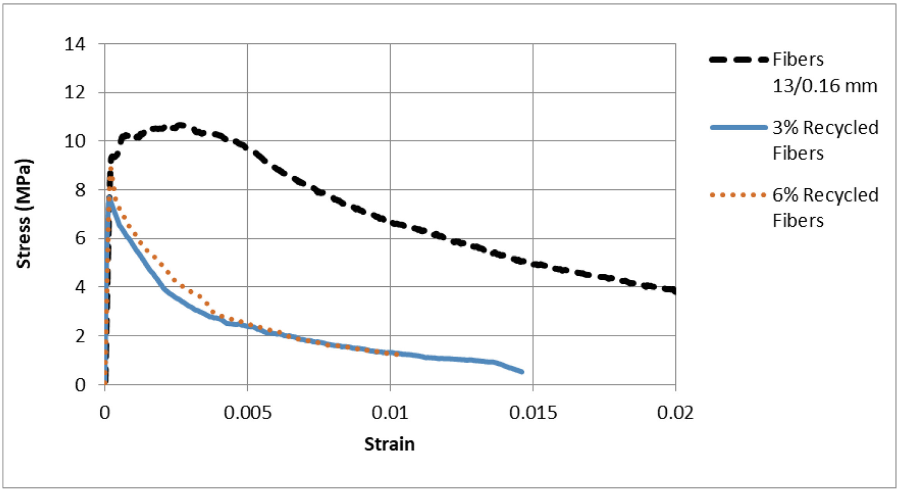


Fig. 5. Comparison of the results for the different types of steel fibers

Table 3. Results for the different types of fibers

Fibers	Tensile Strength (MPa)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
3% Recycled	7.6	167	56
6% Recycled	8.9	184	57
3% Conventional	10.7	164	56

provide a crack bridging effect leading to higher stress values in the post-cracking region. To the contrary, the material presented strain softening for both percentages 3% and 6% of the recycled fibers UHPFRC. This is attributed to the insufficient bond between the fiber and the cementitious matrix. In case of unprocessed recycled fibers, the presence of small amounts of rubber, even after washing, has detrimental effect to the interfacial properties and to the pull-out resistance of the fibres.

Appropriate treatment of the recycled fibres and selection of fibres with sufficient length can lead to significant enhancement of the mechanical characteristics of UHPFRC [18]. Based on Tlemat et al. [23], the tensile stress, using recycled fibres is increased for higher length/diameter ratio. In this investigation only short fibers have been used. Further study with the use of fibers of various lengths is suggested.

From the experimental results in Table 3, it can be seen that almost the same compressive strength was achieved for the different types of fibers and the same contents. Therefore, the compressive strength using 3% recycled fibers was 167 MPa and the compressive strength using 3% conventional fibers was 164 MPa. Very high compressive strength was achieved using 6% recycled fibers at 184 MPa.

5 Conclusions

For the production of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) high quantities of cement and fibers are used. Ground Granulated Blast Furnace Slag (GGBS) was used as a part replacement of cement and unprocessed recycled steel fibers from car tyres were used to produce a more sustainable UHPFRC. The results of the present study indicate that the compressive of UHPFRC is not affected significantly for GGBS contents up to 30%. A linear reduction of the compressive strength was observed for higher percentages of GGBS. The addition of unprocessed recycled steel fibers on the other hand, resulted in an increase in the compressive strength of UHPFRC similar to those achieved using conventional steel microfibers. In tension, the UHPFRC with the unprocessed recycled fibers showed a reduced strength in the post-cracking region and subsequent strain softening which is attribute to the poor bond at the matrix-to-fiber interfaces due to the presence of remaining amounts of rubber. The importance of the appropriate cleaning of the fibres and the reduction of the short-length fibres has been highlighted in the literature [18]. Future studies on UHPFRC should focus on the fibre treatment processes for the improvement of the fiber-to-cementitious matrix interfacial bond in addition to the use of fibers with various lengths. The present study focused on the performance of GGBS as part replacement of CEM I in order to identify the optimum percentage without significant loss of the performance of the UHPFRC. Further study is suggested in the use of different types of cement, such as CEM III, which contains GGBS or early strength cements. Also, investigation of the performance of UHPFRC using GGBS in different ages is suggested.

Acknowledgments. The authors would like to acknowledge TWINCON Ltd for providing the general purpose (unprocessed) recovered steel fibres which were used in this study.

References

1. Paschalis, S., Lampropoulos, A.: Mechanical performance and cost correlation of Ultra High Performance Fiber Reinforced Concrete (UHPFRC). In: 19th Congress of IABSE Stockholm, IABSE (2016)
2. Association Française de Genie Civil (AFGC), Ultra High Performance Fiber Reinforced Concrete-Interim Recommendations. Bagneux, France (2013)
3. Nicolaides, D., Kanellopoulos, A., Petrou, M., Savva, P., Mina, A.: Development of a new Ultra High Performance Fibre Reinforced Cementitious Composite (UHPFRCC) for impact and blast protection of structures. Constr. Build. Mater. **95**, 667–674 (2015)
4. Abbas, S., Soliman, A.M., Nehdi, M.L.: Exploring mechanical and durability properties of ultra-high performance concrete incorporating various steel fiber lengths and dosages. Constr. Build. Mater. **75**, 429–441 (2015)
5. Ferrara, L., Ozyurt, N., Di Prisco, M.: High mechanical performance of fiber reinforced cementitious composites: the role of casting-flow induced fiber orientation. Mater. Struct. **44**, 109–128 (2011)
6. Paschalis, S., Lampropoulos, A.: Fiber content and curing time effect on the tensile characteristics of ultra high performance fiber reinforced concrete. Struct. Concr. **18**, 577–588 (2017)

7. Safdar, M., Matsumoto, T., Kakuma, K.: Flexural behavior of reinforced concrete beams repaired with Ultra High Performance Fiber Reinforced Concrete (UHPFRC). Compos. Struct. **157**, 448–460 (2016)
8. Paschalis, S., Lampropoulos, A.: Developments in the use of Ultra High Performance Fiber Reinforced Concrete as strengthening material. Eng. Struct. **233**, 111914 (2021)
9. Bruhwiler, E., Denarie E.: Rehabilitation of concrete structures using Ultra-High Performance Fibre Reinforced Concrete. In: The Second International Symposium on Ultra High Performance, Kassel, Germany (2008)
10. Cementitious Slag Makers Association (CSMA), Embodied of UK Cement, additions and cementitious material. https://ukcsma.co.uk/wp-content/uploads/2016/08/Factsheet_18_CO2e_of_Cementitious_Materials_2012.pdf. Accessed 7 Feb 2023
11. Mohan, A., Hayat, M.T.: Characterization of mechanical properties by preferential supplant of cement with GGBS and silica fume in concrete. Mater. Today Proc. **43**(2), 1179–1189 (2021)
12. Elavarasan, S., Priya, A.K., Ajai N., Akash, S., Annie, T.J., Bhuvana. G.: Experimental study on partial replacement of cement by metakaolin and GGBS. Mater. Today Proc. **37**(2), 3527–3530 (2021)
13. Elchalakani, M., Tarek, A., Abu-Aisheh, E.: Sustainable concrete with high volume GGBFS to build Masdar City in the UAE. Case Stud. Constr. Mater. **1**, 10–24 (2014)
14. Shaaban, I.G., Rizzuto, J.P., El-Nemr, A., Bohan, L., Ahmed, H., Tindyebwa, H.: Mechanical properties and air permeability of concrete containing waste tyres extracts. J. Mater. Civil Eng. ASCE **33**(2) (2021)
15. Pilakoutas, K., Neocleous, K., Tlemat, H.: Reuse of tyre steel fibres as concrete reinforcement. Proc. ICE Eng. Sustain. **157**(3), 131–138 (2004)
16. Neocleous, K., Tlemat, H., Pilakoutas, K.: Design issues for concrete reinforced with steel fibers, including fibers recovered from used tires. J. Mater. Civil Eng. **18**(5), 677–685 (2006)
17. Aiello, M.A., Leuzzi, F., Centonze, G., Maffezzoli, A.: Use of steel fibres recovered from waste tyres as reinforcement in concrete: pull-out behaviour, compressive and flexural strength. Waste Manage. **29**, 1960–1970 (2009)
18. Isa, M.N., Pilakoutas, K., Guadagnini, M., Angelakopoulos, H.: Mechanical performance of affordable and eco-efficient ultra-high performance concrete (UHPC) containing recycled tyre steel fibres. Constr. Build. Mater. **255**, 119272 (2020)
19. Al-musawi, H., Figueiredo, F.P., Bernal, S.A., Guadagnini, M., Pilakoutas, K.: Performance of rapid hardening recycled clean steel fibre materials. Constr. Build. Mater. **195**, 483–496 (2019)
20. The concrete society, Ground granulated blast furnace slag. https://www.concrete.org.uk/. Accessed 1 Nov 2022
21. Nicolaides, D.: Fracture and Fatigue of CARDIFRC, Ph.D. thesis. Cardiff, Cardiff University (2004)
22. European Tyre Recycling Association. http://www.etra-eu.org/. Accessed 1 Nov 2022
23. Thlemat, H.: Steel fibers from waste tyres to concrete; testing, modelling and design, Ph.D. thesis, University of Sheffield (2004)